Turbulence statistics of natural airflow within a large Open Top Chamber

ZHANG Jun-hui, HAN Shi-jie, SONG Guo-zheng
Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, P. R. China

Abstract: The turbulence statistics parameters (variables) of natural airflow within a large Open Top Chamber (OTC), 4 m in high height and 3 m in diameter, were measured with a three-dimensional ultrasonic anemometer/ thermometer at Research Station of Changbai Mountain Forest Ecosystems Jilin Province, China in May 2004, for improving the field application of OTP. Results showed that because of the physical limitation, turbulence within OTC exhibited unique map compared with that of natural environments. There were clear daily patterns for most parameters. Turbulence here seemed to be isotropic and closely linked at all directions. Shape of eddies looked like a 'cylinder' which was very similar to the shape of OTC. Continuous airflow was always interpreted by large scale eddies from top of OTC and showed high interactive intermittence at all directions.

Keywords: Open top chamber; Turbulence density; Time and length scales; Intermittence; Buoyancy
CLC number: S716.4 **Document Code:** A **Article ID:** 1007-662X(2005)04-0303-03

Introduction

At present, there are three options for researchers to investigate response of plants to climate change by manipulative experiments, namely open-field CO_2 enrichment (FACE) system (McLeod *et al.* 1988), fully-enclosed chamber systems (Lucas *et al.* 1987) and open-top chamber systems (OTC), (Heagle *et al.* 1973). Among these techniques, open-top chambers have been most widely used without high cost and complex environmental controls of closed chambers (Jones *et al.* 1984) or high cost of CO_2 required by free air release.

Compared with FACE systems, open-top chambers alter the microclimate within them (Leadley *et al.* 1993). Measurements of micro environmental variables, e.g. temperatures, humidity and radiation, etc., with gradient ways show that there are gradient changes in all factors across the chamber (Wang *et al.* 1994; De *et al.* 1998) which may own in large part to the altered exchange properties, compared with the natural environment (Ham *et al.* 1991). Measurement and control of the key physical variables is complex and conflict. The detailed studies on fluid dynamics and exchange properties, particularly turbulence maps, will help to minimize this problem and to improve the performance of open-top chamber as a field experimental tool (Leadkey *et al.* 1993). However, very few studies on these processes within OTC have been reported.

On the basis of interior exchange data by using a three-dimensional ultrasonic anemometer/thermometer in May 2004, this paper intends to present the detailed statistics of natural turbulence within a large open-top chamber and to provide basic information of improving field application of OTC.

Methods

Site and data collection

Measurements were conducted in a large OTC situated at the Research Station of Changbai Mountain Forest Ecosystems, Chinese Academy of Sciences (42°24'N, 128°28'E, 738 m in elevation; Antu County, Jilin Province, China). The chamber, 4 m in height and 3 m in diameter, is framed with steel structure and covered with glass wall. Five-year-old *Pinus koraiensis* seedlings, with an average canopy height of about 30 cm, were planted within the chamber. No CO_2 treatment was made in the measured chamber. A 2.5-m-tall steel pole was installed at the centre of OTC bottom to support the OTC. A three- dimensional (u, v, w) sonic anemometer (CSAT32, Campbell Inc., USA) was mounted at 2 m height on the steel pole, and a sensor head was installed at 0.25 m away from the pole. Data was continuously sampled at 10 Hz and recorded by a laptop computer from August First to August Twentieth, 2004. Raw data were sliced into 30-min segments for subsequent analysis.

Data analysis

Linear trends were removed before the following calculations. *Local atmospheric stability* was characterized by the $\varsigma = z/L$, where, L is Monin-Obukov length,

$$L = \frac{-\overline{\theta_v}\left(\overline{u'w'}^2 + \overline{w'v'}^2\right)^{3/4}}{kg\,\overline{w'\theta'_v}} \tag{1}$$

where, k is Von Karman constant (assumed=0.4), g is the acceleration velocity due to gravity, θ is the potential temperature, and u, v, and w components of wind in this paper.

By substituting u, v and w for x in following equations, *standard deviations* of velocity components were calculated as

$$\sigma_x = \left(\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2\right)^{1/2} \tag{2}$$

Skewnesses of velocity components, Sk_x were calculated as

Foundation Item: This research was supported by Project of Key program of the National Natural Science Foundation of China (90411020) and National Basic Research Program of China (2002CB412502).
Biography: ZHANG Jun-hui (1973-), male, Ph. D., in Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, P. R. China.(E-mail:jhzhang@iae.ac.cn)
Received date: 2005-04-20; **Accepted data:** 2005-08-28
Responsible editor: Zhu Hong

$$Sk_x = \overline{x'^3}/\sigma_x^3 \quad (3)$$

Kurtosis of velocity components, Kr_x, were calculated as

$$Kr_x = \overline{x'^4}/\sigma_x^4 \quad (4)$$

Integral time scales τ of velocity components, were estimated as

$$\tau_x = \int_0^\infty R_x(\xi)d\xi \quad (5)$$

where, $R_x(\xi)$ is the eulerian autocorrelation function at time delay ξ.

Taylor Micro time scales, λ, were estimated as coefficient of following regression formula,

$$R_x(\xi) = 1 - \xi^2/\lambda_x^2 \quad (6)$$

Results

Standard deviation of wind components

Standard deviations of all wind components showed clear diurnal patterns (Fig. 1). Daytime values were higher than nighttime ones. Average values (Table 1) were lower than the reported values of natural environment (Baldocchi *et al.* 1988; Raupach *et al.* 1996; Zhang 2002). It implies that turbulence density within OTC is far smaller than that in natural environments.

In contrast to the nature environments where σ_w is much less than σ_u and σ_v (Baldocchi *et al.* 1988; Amiro 1990; Raupach *et al.*; 1996; Zhang 2002), standard deviations of all wind components here were very close to each other.

Table 1. Statistics of standard deviation of wind components

Items	Average	Variance	Max.	Min.
σ_u	0.09	0.06	0.26	0.02
σ_v	0.10	0.06	0.31	0.03
σ_w	0.10	0.06	0.30	0.03
σ_u/σ_v	0.90	0.10	1.15	0.65
σ_u/σ_w	0.90	0.11	1.24	0.56
σ_v/σ_w	1.01	0.12	1.58	0.62

Notes: σ_u, σ_v and σ_u are standard deviation of wind components u, v and w

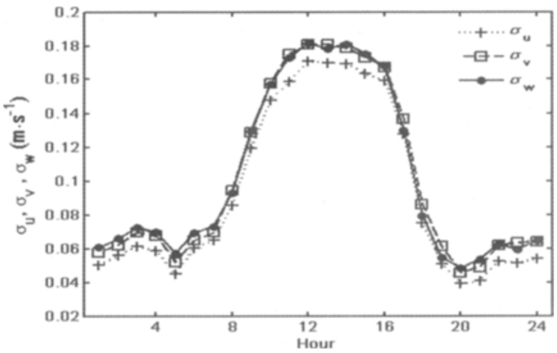

Fig. 1 Averaged daily course of standard deviation of wind components within OTC from 1 Aug. to 20 Aug., 2004.

Time scales and length scales

Taylor micro scale (λ) characters contribution of turbulence kinetic energy (TKE) to enstrophy (Hu 1995) and size of minimum eddy transfer energy from the inertial subrange to the dissipation range. Within OTC, daytime ($\lambda_{u,v}$) was higher than nighttime ones (Table 2), while nighttime (λ_w) was almost equal to its daytime value. Horizontal advection was restricted by the chamber and turbulence was dominant process for horizontal transport. Daily course of horizontal turbulence density may be responsible for the daily pattern of $\lambda_{u,v}$.

Integral time scales and length scales characterize the energy-containing range of eddy time and spatial scales. The very low mean velocities within OTC imposed conditions where Taylor's 'Frozen eddy' hypothesis does not hold, and length scales based on u are no more meaningful than those based on the standard deviations (Amiro 1990). Following Amiro (1990), Length scales ($L_{u,v,w}$) were defined as the product of turbulence density ($\sigma_{u,v,w}$) and time scales ($\tau_{u,v,w}$).

According Table 2, at daytime, time scale and length scale of vertical component were much larger than that of horizontal components. Eddy looked like a 'cylinder' and was very similar to the shape of OTC.

During nighttime, time scales of horizontal components were much larger than that of daytime, but for the reduction of turbulence density during night, the length scales increase not much as time scales.

Although there was not obvious difference between nighttime value (τ_w) and daytime value, the nighttime value (L_w) was much lower than the daytime values for the big reduction of σ_w.

Table 2. Averaged Taylor micro time scales, integral time scales and length scales within a large OTC .

Items	λ (s)		τ (s)		L (m)	
	Day	Night	Day	Night	Day	Night
u	0.019	0.008	3.08	18.44	0.44	0.83
v	0.017	0.008	2.92	19.56	0.45	0.85
w	0.005	0.004	17.70	20.04	2.98	1.11

Skewness and Kurtosis

Skewness expresses the degree of asymmetry of a probability distribution. As shown in Fig. 2a, there was obvious daily pattern for Sk_w though the magnitude was little. Sk_w for most runs were negative. There were not obviously daily pattern for $Sk_{u,v}$ while values were almost positive. This was very similar to the airflow around forest canopy where u, v was positively and w was negatively skewed by large-scale downward movements (Shaw and Seginer *et al.* 1987).

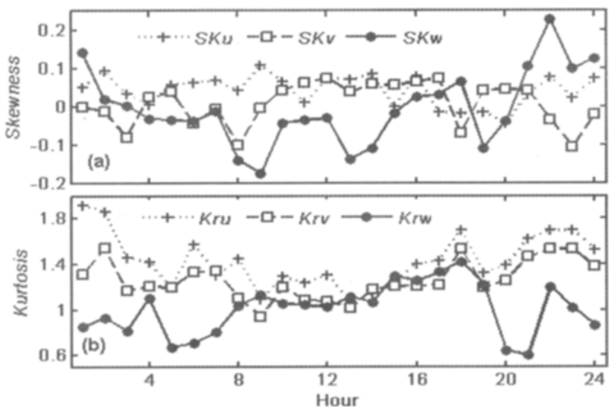

Fig. 2 Averaged daily course of Skewness (a) and Kurtosis (b) of wind components within OTC from 1 Aug. to 20 Aug., 2004

Kurtosis is a measurement of peakness or flatness of a probability distribution, with a value of 3 for Gaussian distributions. This parameter can be used to indicate the intermittent of airflow (Shaw 1985). Fig. 2b showed the difference between Kurtosis values for Gaussian distribution and that of *u*, *v*, and *w* velocity components. The Kurtosis values of all components for all runs were over 3. Kurtosis of wind components were highly correlated (Table 3). The airflow was characterized by high interactive intermittence at all directions.

Table 3. Correlation equations among Kurtosis of wind components

Equations	R^2	N	P
$Kr_u = 0.688\ Kr_v + 0.644$	0.418	648	<0.001
$Kr_u = 0.510\ Kr_w + 0.911$	0.237	648	<0.001
$Kr_v = 0.495\ Kr_w + 0.639$	0.253	648	<0.001

Notes: Kr_u, Kr_v Kr_w are kurotisis of wind components u,v and w.

Summary and discussion

We presented the turbulence statistics parameters within a Large OTC measured with a three-dimensional ultrasonic anemometer/ thermometer in May 2004. This will provide basic information to improve field application of OTC.

Map of basic turbulence variables

For the physical limitation, turbulence within OTC exhibited unique map, compared with those of natural environments. There were clear daily patterns for most parameters. Turbulence here seemed to be isotropic and closely linked at all directions. Spatial structure of eddies looked like a 'cylinder' and were very similar to the shape of OTC. Continuous airflow was always interpreted by large scale eddies from top of OTC and showed high interactive intermittence at all directions.

Table 4. Statistics of Local atmospheric stability (ζ) within OTC

Terms	Day	Night
Mean	-2.02	-6.50
Skewness	-2.96	-1.95

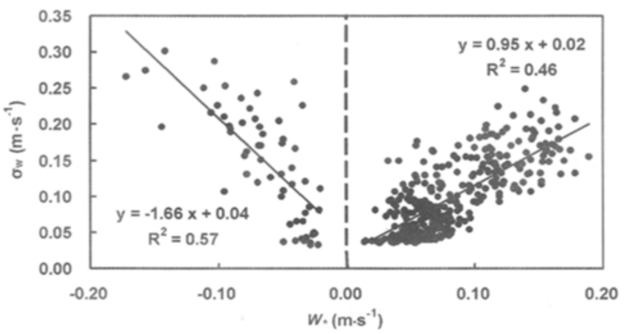

Fig. 3 Correlation between the velocity scales for buoyancy (W_*) and standard deviation of vertical wind speed (σ_w)

Mechanisms for turbulence within OTC

In general, buoyancy and mechanical shear are dominant mechanisms for turbulence production and maintenance at local scales (Stull 1988). The stability indicator (ζ), which characters the ratio of buoyancy to mechanical shear terms of TKE budget equation, was greater than 1 and negatively skewed all-day (Table 4). Daytime and nighttime percentages of data points for $|\zeta|\geq 1$ were 67 and 82, respectively. These suggest that buoyancy was the dominant mechanism for turbulence within OTC. Close correlation between the velocity scales for buoyancy (W_*), the velocity scales for buoyancy, and standard deviation of vertical wind speed (σ_w) also supported this inference (Fig. 3).

Manipulative experiments are absolutely necessarily to predict the behavior of terrestrial ecosystems under the changing climate. Open-top chambers have been most widely used without high cost or complex environmental controls. The basic information by this study and coming measurements for turbulent properties at multipoint within chambers will help to minimize the problem of measurement and control of the key physical variables in its field applications.

References

Amiro, B.D. 1990. Comparison of turbulence statistics within three boreal forest canopies [J]. Boundary-Layer Meteorology, **51**(1/2): 99–121.

Baldocchi, D.D. and Meyers, T.P. 1988. Turbulence structure in a deciduous forest [J]. Boundary-Layer Meteorology, **43**(4): 345–364.

De Angelis, P. and Scarascia-Mugnozza, G. 1998. Long-term CO_2 enrichment in a mediterranean natural forest: an application of large open top chambers [J]. Chemosphere, **36**(4/5): 763–770.

Ham, J. and Owensby, C. 1991. Simulating confounding CO_2 and chamber effects in open to field chamber for CO2 enrichment studies [C]. In: Agronomy abstracts. American Society of Agronomists, Madison, Wisconsin 53711 USA, p18.

Heagle, A.S., Body, D.E. and Heck, W.W. 1973. An open top field chamber to assess the impact of air pollution on plants [J]. J. Environ. Qual., **2**(2): 365–368.

Hu Fei. 1995. Turbulence, intermittence and atmospheric boundary layer [M]. Beijing: Science publishing Press, p 77.

Leadley, P.W. and Drake, B.G., 1993. Open top chambers for exposing plant canopies to elevated atmospheric CO_2 and for measuring net gas exchange [J]. Vegetation, **104/105** (1), 3–15

Lucas, P.W., Cottam, D.A., Mansfield, T.A. 1987. A large-scale fumigation system for investigating interactions between air pollution and cold stress on plants [J]. Environ. Pollut., **43**(1): 15-28.

McLeod, A.R. and Baker, C.K. 1988. The use of open field systems to assess yield response to gaseous pollutants [C]. In: Heck, W.W., Taylor, O.C. and Tingey, D.T. (eds.) Assessment of crop loss from air pollutants. Elsevier Applied Science, Barking, pp. 181–210.

Norris, T., Wilkinson, D., Lockwood, A., *et al.* 1996. Performance of a controlled-ventilation open-top chamber for climate change research [J]. Agricultural and Forest Meteorology, **78**(3): 239–257.

Raupach, M.R., Finnigan, J.J. and Brunet, Y. 1996. Coherent eddies and turbulence in vegetation canopies: The mixing-Layer analogy [J]. Boundary-Layer Meteorology, **78**(3/4): 351–382.

Shaw, R.H. 1985. On diffusive and dispersive fluxes in forest canopies [C]. In: B.A. Hutchison and B.B. Hicks (eds.), the Forest-Atmospheric Interaction. D. Reidel. Co., Dordrecht., p407–419.

Shaw, R.H. and Seginer, I. 1987. Calculation of velocity skewness in real and artificial plant canopies [J]. Boundary-Layer Meteorology, **39**(4): 315–332

Stull, R.B., 1988. An Introduction to boundary layer meteorology [M], Dordrecht: Kluwer Academic publishers, 153–166.

Wang Chunyi, Gao Suhua and Liu Jiangge. 1994. The structure and performance of OTC-1 open top chamber [J]. Advance in Environmental Science, **2**(3): 19–31.

Zhang Junhui, Ding Zhihui., Han Shijie, *et al.* 2002. Turbulence regime near the forest floor of a mixed broad leaved/Korean pine forest in Changbai Mountains [J]. Journal of Forestry Research, **13**(2): 119–122.